

Massively Clustered CubeSats NCPS Demo Mission

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Abstract. Technologies under development for the proposed Nuclear Cryogenic Propulsion Stage (NCPS) will require an un-crewed demonstration mission before they can be flight qualified over distances and time frames representative of a crewed Mars mission. In this paper, we describe a Massively Clustered CubeSats platform, possibly comprising hundreds of CubeSats, as the main payload of the NCPS demo mission. This platform would enable a mechanism for cost savings for the demo mission through shared support between NASA and other government agencies as well as leveraged commercial aerospace and academic community involvement. We believe a Massively Clustered CubeSats platform should be an obvious first choice for the NCPS demo mission when one considers that cost and risk of the payload can be spread across many CubeSat customers and that the NCPS demo mission can capitalize on using CubeSats developed by others for its own instrumentation needs. Moreover, a demo mission of the NCPS offers an unprecedented opportunity to invigorate the public on a global scale through direct individual participation coordinated through a web-based collaboration engine. The platform we describe would be capable of delivering CubeSats at various locations along a trajectory toward the primary mission destination, in this case Mars, permitting a variety of potential CubeSat-specific missions. Cameras on various CubeSats can also be used to provide multiple views of the space environment and the NCPS vehicle for video monitoring as well as allow the public to “ride along” as virtual passengers on the mission. This collaborative approach could even initiate a brand new Science, Technology, Engineering and Math (STEM) program for launching student developed CubeSat payloads beyond Low Earth Orbit (LEO) on future deep space technology qualification missions.

Keywords: Nuclear Propulsion, NCPS, SLS, Mars, CubeSat.

INTRODUCTION

The capabilities of the NASA Space Launch System (SLS) open up the mission design space for crewed deep space exploration missions in the 2020-2040 timeframe. The SLS is to use a Cryogenic Propulsion Stage (CPS) as its second stage for space exploration. However for crewed missions to Mars, it has been proposed to replace the CPS with a Nuclear Cryogenic Propulsion Stage (NCPS). To this end, a first generation NCPS, based on Nuclear Thermal Propulsion (NTP), is being developed to provide high thrust at a specific impulse above 900s, roughly double that of state of the art chemical engines (Houts, 2013) that the CPS is based on. The NCPS will need to be placed by the SLS into a 407 km high parking orbit, for earth safety as well as for checkout of the NCPS and payload systems, before commencing the NCPS burn.

The NCPS will involve many first generation technologies that will require a demonstration mission before they can be qualified over distances and time frames that are representative of a crewed Mars mission. An initial un-crewed NCPS demonstration mission will be an historic event, representing the first time a space vehicle of such high performance (high thrust at high specific impulse) has ever flown. But for this historic first to be achievable in the near term, in a way that allows for sustainable NCPS follow on missions, it is important to plan the NCPS demo so that it will be a low cost (affordable) mission that will strengthen public support of NASA’s exploration mission, have support from multiple government agencies, and involve both the commercial aerospace and academic

communities. In this paper, an NCPS demo mission is proposed that would carry and/or release multiple small CubeSats or like-size payloads. Individually, these CubeSats would be built and funded by a mixture of government, commercial aerospace and academic sources. Released CubeSats may or may not be directed along trajectories aimed toward Mars. For example, while still in parking orbit, some CubeSats can be launched prior to vehicle transfer orbit insertion. These CubeSats can be used to serve a dual purpose. Launched primarily for scientific studies, they can also be used to inspect the NCPS vehicle for possible launch damage. At a parking orbit 407 km above the Earth, where the atmosphere has little influence upon a spacecraft's orbit, CubeSat missions of longer duration than possible at LEO would allow long term scientific studies to be conducted as well as contribute to the collective demonstration of NCPS technologies needed for crewed Mars missions.

This paper represents a first-quick-look at a proposed Massively Clustered CubeSats NCPS demo mission and is not intended to present a final product. A key point of this paper is that it is reasonable to expect interest from several government agencies in partnering on the proposed mission, as well as from the commercial aerospace and academic communities, being that many of these groups are already planning for interplanetary (and even interstellar) CubeSat missions and/or need the technology improvements that the NCPS demo mission would validate.

CUBESATS

Vanguard missions of historic significance are generally not cheap. But CubeSats offer a hope for responding to this challenge by activating academic and aerospace communities in a way that other approaches cannot. CubeSats are a class of research spacecraft called nanosatellites. The cube-shaped satellites (aka, CubeSats; for example, FIG. 1) are approximately 10 cm cubes, having a volume of about one liter, that weigh 1-2 kg. A standardized format lends itself to a clustered platform of many individual CubeSats, and therefore cost and risk sharing for launch. The value of CubeSats has already been well recognized by many organizations. A few examples follow.



Figure 1. Representative CubeSat (from http://www.nasa.gov/directorates/heo/home/CubeSats_initiative.html)

NASA's CubeSat Launch Initiative

NASA's CubeSat Launch initiative (CSLI) provides opportunities for small satellite payloads to fly on rockets planned for upcoming launches and flown as auxiliary payloads on previously planned missions. By providing a progression of educational opportunities including CSLI for students, teachers, and faculty, NASA assists the Nation in attracting and retaining students in STEM disciplines. The research addresses aspects of science, exploration, technology development, education or operations. This strengthens NASA's and the Nation's future workforce.

Further, the CSLI promotes and develops innovative technology partnerships among NASA, U.S. industry, and other sectors for the benefit of Agency programs and projects. NASA thus gains a mechanism to use CubeSats for low-cost technology development or pathfinders.

(From http://www.nasa.gov/directorates/heo/home/CubeSats_initiative.html)

National Science Foundation (NSF): CubeSat-based Science Missions for Geospace and Atmospheric Research

The NSF recognizes that the lack of essential observations from space is currently a major limiting factor in many areas of geospace and atmospheric research. However, with recent advances in sensor and spacecraft technologies, it is now feasible to obtain key measurements from low-cost, small satellite missions. A particularly promising aspect of this development is the prospect for obtaining multi-point observations in space that are critical for addressing many outstanding problems in space and atmospheric sciences. Space-based measurements from small satellites also have great potential to advance discovery and understanding in geospace and atmospheric sciences in many other ways. The overarching goal of the NSF CubeSat program is to support the development, construction, launch, operation, and data analysis of small satellite science missions to advance geospace and atmospheric research. Equally important, the NSF CubeSat program provides essential opportunities to train the next generation of experimental space scientists and aerospace engineers. To facilitate launch of the satellites as secondary payloads on existing missions, the focus of the program is on CubeSat-based satellites with science missions to include satellite development, construction, testing and operation as well as data distribution and scientific analysis.

(From <http://www.nsf.gov/pubs/2012/nsf12536/nsf12536.htm>)

Navy: Novel CubeSat Payloads for Naval Space Missions

In 2012, the US NAVY issued a SBIR topic to develop novel CubeSat payloads for Naval space missions. The US Navy realizes that nano-satellites are popular among universities and gaining momentum with commercial and government organizations. Standards based satellite buses and deployment mechanisms, such as the CubeSat and Poly Pico-satellite Orbital Deployer (P-POD), have stimulated growth in the area. Small satellites have proven capable and cost effective in many areas traditionally dominated by large satellites, however many challenges remain. Beyond state of the art research is needed to drastically reduce the size, weight and power of payloads that have traditionally performed naval space missions on much larger satellites. Traditional Naval space missions include, but limited to, narrowband communications (UHF Follow On, Mobile User Objective System), astrometry (Joint Milli-Arcsecond Pathfinder Survey), and ocean sensing (GEOfetic SATellite, GEOSAT Follow On). Smaller, more cost effective satellites will enable the Navy to continue vital space missions despite limited resources.

(From http://www.navysbir.com/n12_2/N122-146.htm)

Also see the work by the Naval Post School (NPS), for example:

- NPS CubeSat Prepares to See Space By Way of New Payload Platform
<http://www.nps.edu/About/News/NPS-CubeSat-Prepares-to-See-Space-By-Way-of-New-Payload-Platform-.html>
- NPS CubeSat Launcher Design, Process and Requirements
<http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA501503>

Clyde Space: A SmallSat Company

The low cost of CubeSats, which makes it easier to fly large numbers of such spacecraft, is opening up potential new applications as well. Craig Clark, CEO of Scottish smallsat company Clyde Space, discussed at the conference

(AIAA/Utah State University Conference on Small Satellites) a concept for a network of 3U CubeSats to provide realtime imagery of the globe. Advanced technologies such as deployable optics would allow such spacecraft to take images with resolutions as sharp as 0.7 meters, he said. “This is all leading to having live images of the Earth for people to view, initially with medium-resolution images” and later moving to higher-resolution images—in effect, he said, a live version of Google Earth.

(From <http://aerospace.engin.umich.edu/newsevents/cubesats-get-big>)

Interplanetary CubeSat Workshop

The 2nd Interplanetary CubeSat (iCubeSat) Workshop (to be held in Ithaca, NY – 28-29 May 2013) will address the opportunities, technical challenges, and practicalities of space exploration with CubeSats. The workshop will provide a unique environment for open practical collaboration between academic researchers, industry professionals, policy makers and students developing this new and rapidly growing field; and welcomes talks on astrodynamics, attitude control and determination systems, citizen science, citizen space exploration, communications, landers, launch opportunities, open source approaches, outreach, payloads, policy, power systems, propulsion, reentry system, ride-shares, science missions, software, standardization, structures, systems engineering and other related topics.

(From <http://www.cubesat.org/>)

NASA's Technology Demonstration Missions

Within their limited size, CubeSat or like-size payloads could also help NASA's Technology Demonstration Missions (TDM) to bridge the gap between need and means, between scientific and engineering challenges and the technological innovations needed to overcome them, between laboratory development and demonstration in space by maturing laboratory-proven technologies in a small flight-ready status. That is, CubeSats could provide a low cost chance for some new technologies to operate in the actual space environment, where to gain operational heritage that reduce risks to future missions by eliminating the need to fly unproven hardware and continue NASA's long history as a technological innovator. Doing so, would allow future NASA missions to pursue bolder and more sophisticated science, enable safe and rewarding human missions beyond low-Earth orbit and enable entirely new approaches to U.S. space operations.

(From http://www.nasa.gov/mission_pages/tdm/main/index.html)

CLUSTERED CUBESATS AS A PRIMARY PAYLOAD

It is envisioned that the payload of a NCPS demo mission could comprise a massive cluster of CubeSats, accommodating 100s of CubeSats comprising the primary payload (verses being the secondary payload as is currently done) with each individual CubeSat being independently funded and developed by various organizations, companies, and academia so as to reduce the total mission cost. Further, by properly selecting CubeSats that carry instrumentation needed by the NCPS demo mission (or directing them to carrying low cost instrumentation as part of the flight package, like radiation dosimeters, temperature gages & etc.), part of the NCPS demo mission instrumentation cost can be levied onto the CubeSats as a whole. For example, but not exclusive to:

- From an academic viewpoint, CubeSats can be sought with the only purpose to monitor conditions of the NCPS vehicle with video as well with other instruments while on board and as they move away from the NCPS.
- From a commercial viewpoint, CubeSats can be sought with the only purpose to provide data on the long term radiation exposure on new space technologies or to demonstrate new space technologies in general (*i.e.*, increase TRLs).

- From NASA mission directorate review point, CubeSats can be sought with the only purpose to increase TRLs of previously unflown technologies or to provide data on a specific object or place in space.
- From NASA publicity viewpoint to invigorate the public, CubeSats size payloads can be sought to carrying cameras which could be access by smart phones and the internet as if one is on board and looking out a window.

Generally speaking, the range of tasks for CubeSat size payloads is near endless compared to the space that could be available on a NCPS demo mission.

SLS EXPLORATION MISSIONS

NASA's Space Launch System (SLS) is an advanced, heavy-lift launch vehicle which will provide an entirely new capability for science and human exploration beyond Earth's orbit. The SLS will be NASA's first exploration-class vehicle since the Saturn V took American astronauts to the moon over 40 years ago. With its superior lift capability, the SLS will expand our reach in the solar system, allowing astronauts aboard the Orion spacecraft to explore multiple, deep-space destinations (for more info see www.nasa.gov/sls). Figure 2 shows a representation of the possible SLS exploration missions to include the Lagrange points, Moon, Asteroids, and Mars. Each of these locations provides an opportunity for CubeSat like and size science missions.

The SLS is to use a Cryogenic Propulsion Stage (CPS) as its second stage for space exploration. However for the Mars manned missions, it has been proposed to replace the CPS by a Nuclear Cryogenic Propulsion Stage (NCPS).



Figure 2. Representative SLS Exploration Missions

To provide a more affordable path, the NCPS will utilize common elements from the CPS as much as possible. The most obvious common infrastructure that can be utilized is cryogenic tanks and long-term liquid hydrogen storage capability. Lightweight structures, avionics, and power systems can be very similar for the CPS and NCPS for the same type of manned mission to Mars. One of the biggest challenges for a mission to Mars will be the Cryogenic Fluid Management (CFM) with multiple mission components coming together in orbit with automated rendezvous over a period of time (months). Zero leakage of liquid hydrogen in the system and especially thru quick disconnects will be essential for both CPS and NCPS to accomplish any long-term mission.

There are many technology requirements that will be similar between the CPS and NCPS, especially since both systems are to utilize cryogenics for propellant. An advantage of the NCPS over the CPS will be the absence of a second propellant tank as it will be a mono-propellant stage, which should offer more opportunity for a large clustering of CubeSats as the main payload. This not to say that a smaller Clustered CubeSats CPS demo mission could not provide a pathfinder for the larger Clustered CubeSats NCPS demo mission, say launching CubeSats to higher orbits, *i.e.*, the Lagrange points or the moon.

EARLY FLIGHT DEMONSTRATION

The Johnson Space Center (JSC) Nuclear Systems Team is exploring options and concepts for a nuclear thermal rocket that could be utilized in an early NCPS demo mission. One option called the “MINI Flight Demo” (FIG. 3) can ideally be used to illustrate a Clustered CubeSats NCPS demo mission. For example, the “966 kg Science Hitchhiker” as shown in FIG. 3 can be replaced with a 50%-50% split between the CubeSat holding/launch/Communication/Power structure and the CubeSats, which for CubeSats weighing ~2 kg would allow (by weight) about 241 possible CubeSats. Although a payload of hundreds of CubeSats is a guess at this point as volume constraints need to be account for, a “MINI Flight Demo” or a similar flight demo illustrates that it should be possible to carrying hundreds of CubeSats for a variety of specific science and technology goals using the SLS/CPS/NPCPS platform.

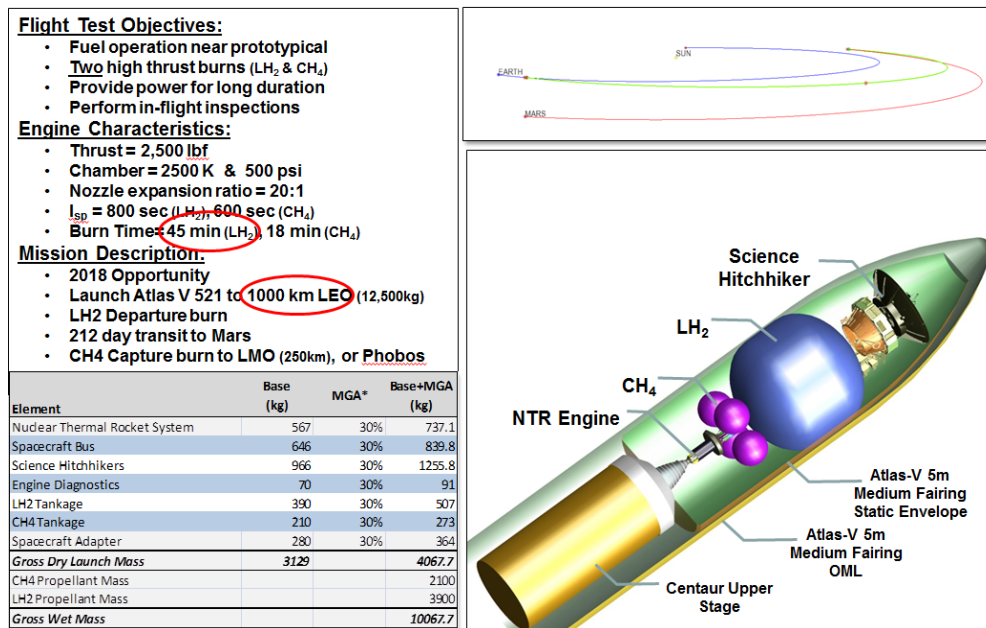


Figure 3. MINI Flight Demo

CubeSat Launch System

The launch system for the clustered CubeSats NPCPS demo mission could be based on other CubeSat launch systems or a totally new launcher specific for the NCPS demo mission could be designed. One example of an already flight qualified CubeSat launch systems is the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) structure and Secondary Payloads (CubeSat launchers) (Crook, 2009) in FIG. 4, which was launch in March 2007 on the U.S. Air Force (USAF) Space Test Program (STP) mission “STP-1”. The ESPA facilitated the use of thousands of pounds of excess payload capacity that, until recently, would have otherwise been wasted. It is easily

seen that the ESPA structure, as shown in FIG. 4, could possibly be enlarged or stacked for more CubeSat (secondary) payloads on a NPCS demo mission.

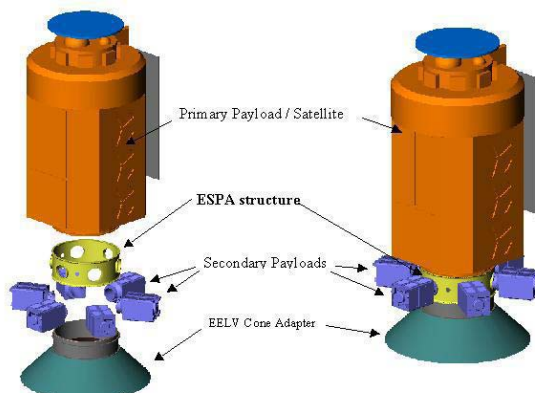


Figure 4. USAF ESPA Integration Diagram for adapting a Multiple CubeSats Launch System as a Secondary Payload.

A CHALLENGE TO INSPIRE THE GLOBAL COMMUNITY

“What would you do if you could place a small personal satellite almost anywhere from a parking orbit 407 km above the earth to an orbit as distant as Mars?”

Domestically, under programs such as the NASA CSLI, for example, research conducted by CubeSats on the NCPS demo mission can address aspects of science, exploration, technology development, education or operations. Results could then be publicized through such venues as a future NETS conference or the iCubeSat Workshop. Public education initiatives such as STEM can also benefit by inspiring young minds with this challenge, creating a new STEM program, involving interstellar CubeSats carried aboard this and other future propulsion demonstration missions, that would be an impressive item on any student resume. Public interest can also be engaged through virtual tourism where online customers might pay for time at the controls of small independent CubeSats on route to Mars, pointing and focusing cameras at will, for truly out of this world images. And let us not forget the interest companies would have for a chance to put their logo in front of that camera lens. But given the globally interconnected culture that we all live in, limiting participation in such a historic mission to a single nation would miss out on the truly unique potential offered by a payload of hundreds of CubeSats.

The Massively Clustered CubeSats platform is a payload for the NCPS demo mission that lends itself well to open source architectures. Architects of the challenge would describe the framework, standards, interface control, review processes, safety protocols, etc., that would be made available globally, without charge, through a web-based collaboration engine. Collaboration would enable creative individuals throughout the world, inspired by the challenge, to independently or collectively develop their own CubeSats and/or systems of CubeSats. This interactive global community of developers would work openly together on any number of coordinated CubeSat projects in much the same way that open source software developers work together to write code that can be combined seamlessly within a common and open framework.

Web-based collaboration can take many forms. It could be as simple as sharing expertise and experiences across the planet. Or, it could be as elaborate as a coordinated effort to develop an organized system of CubeSats designed to collectively interact with one another in a distributed manner to accomplish a common task – a synergistic relationship among the CubeSats themselves that mirrors the global synergy of the designers who create them. Such a collective system might possess a parallel computing architecture similar to cluster computing, sharing not only computing resources, such as data, memory, communication and processing capability, but also physical resources,

such as power and propellant, should that be desirable. Many types of parallel architectures, even reconfigurable ones, are possible. An excellent early example of a task well suited to a cooperative approach is the recent GRAIL mission in which two spacecraft orbiting earth's moon flew in formation and shared data. Other examples include a deep space relative navigation concept based on data packets embedded within inter-spacecraft communication that otherwise has no impact on normal spacecraft operations, and the autonomous on-orbit servicing of spacecraft by other spacecraft for life extension and upgrade purposes.

Within this architecture, the NCPS demo mission would be an extensible one. Extensibility is a system design principle where the implementation takes into consideration future growth. Applying this principle would allow NCPS mission capabilities to grow along with CubeSat development. For example, CubeSats monitoring vehicle health and status as well as providing redundant system capabilities, and even effecting repairs, can enhance the NCPS mission and improve reliability.

To implement a global web-based collaboration properly, a separate kind of challenge will be faced by NASA. For as the architect, NASA will need to define the open source spacecraft architecture, along with the rules of collaboration, but carefully crafted so as not to overly constrain the global CubeSat developer community.

To implement a global web-based collaboration properly, NASA will face a separate challenge. As the architect, NASA will define the open source spacecraft architecture, along with the rules of collaboration. This must be done carefully so as not to overly constrain the global CubeSat developer community. After completion of the architecture design, it is important that NASA allow CubeSat development to take on a life of its own with little or no oversight. Only in this way, with the global community of CubeSat developers free to interactively create within pre-established constraints, will concepts and capabilities unimagined by NASA emerge. In fact, the successful open management of independent collaborators is not completely foreign to NASA. Precedence for this approach was set in 2005 when the Centennial Challenges Program was introduced, which effectively and efficiently leverages independent participants to accomplish NASA's goals without NASA oversight.

(See: http://www.nasa.gov/offices/oct/stp/centennial_challenges/index.html)

CONCLUSION

Universally, CubeSats are being aggressively looked at to replace scientific and engineering payloads normally flown on much larger space platforms. By Moore's Law, observed over the history of computing hardware, the doubling of the scale of electronic integration approximately every two years, ensures that CubeSat capabilities will continue to expand. Over time CubeSat technology will provide information and perform tasks that presently cannot be acquired or done as quickly due to cost, representing a technology that could revolutionize how we test new technologies and explore space with unmanned systems. Spreading payload cost and risk across many CubeSat customers, and capitalizing on CubeSat instrumentation for NCPS demo mission needs, makes this important nuclear propulsion demonstration more realizable. Therefore, a Massively Clustered CubeSats NCPS demo mission seems to be an obvious first mission choice.

Furthermore by engaging the public through direct participation, both domestically and internationally, as collaborative researchers and scientists, and as students and tourists, widespread interest can be generated, helping to create the needed political support to promote nuclear propulsion for manned and unmanned spacecraft.

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